Virtual power plant: A review on Components, Models, Types and Scheduling

Alireza Zare[1, *] - Mohammad Agha Shafiyi [2]- Sasan Azad [3]
[1] Shahid Beheshti University Alirezazarenumber1@gmail.com
[2] Shahid Beheshti University shafiyi@hotmail.com
[3] Shahid Beheshti University sa_azad@sbu.ac.ir

ABSTRACT

In the upcoming years, the integration of expanding distributed generations (DGs) and Renewable Energy Sources (RESs) with Energy Storage System (ESS) facilities and also Demand Response Programs (DRP) necessitates the presence of an adaptive power system. A virtual power plant (VPP) stands as an advanced power generation technology that streamlines and enhances generation, network limitations, energy storage devices, and demands. It brings substantial enhancements in power system flexibility, enhances the efficient use of distributed generations on the user-side, and promotes advancements in wholesale markets. Despite its promise, VPP is presently in its nascent phase of development. These *aforementioned technologies are changing the energy landscape, with decentralized energy generation through virtual power plants (VPPs) idea becoming a major trend. VPPs combine small-scale distributed units to act as a single and independent entity. This study examines key issues related to VPPs, including definitions, components, optimization, scheduling problem and types such as commercial VPPs and technical VPPs.*

Keywords: Virtual power plant, Renewable energy, Distributed energy resource, Scheduling, Energy Storage System

1. INTRODUCTION

Over the recent decades, there has been a notable increase in Distributed Generations (DGs), Renewable Energy Sources (RESs), Energy Storage Systems (ESSs) at the distribution level, and Demand response (DR) programs, presenting new challenges for network operators while also providing a transformative opportunity for the grid. Modern DG technologies, incorporating RESs, have undergone significant advancements, such as improved solar cell efficiency, higher wind generator capacities, the evolution of advanced Combined Heat and Power (CHP) systems, progress in fuel cell technologies, enhanced efficiency and capacity of ESSs, and the introduction of innovative RESs like tidal generators and small hydro generators [1].

Meanwhile, the ongoing progression towards the liberalization of the electricity market, transitioning from a monopolistic system to competitive market frameworks, is garnering increasing attention [2]. In light of these dual trends, the operation of a large quantity of DER units under market conditions are unavoidable, presenting new challenges that must be tackled, including:

- Market participation: Despite being viewed as small, adaptable power sources, storage technologies, and controllable loads [3], DERs are typically restricted from entering the existing electricity market [4].

- Stochastic characteristics: Given that numerous DER technologies such as solar panels and wind turbines rely on weather conditions, their variable output is deemed non-dispatchable, limiting their role in grid operations and leading to economic penalties stemming from unforeseen imbalances.

- Isolation: Many DER units operate independently due to differing ownership structures. Collaboration and communication between adjacent DER units are often lacking, constraining the capacity of DERs to meet local demands rather than the broader grid requirements.

One strategy to tackle these challenges is to aggregate multiple DER units within a Virtual Power Plant (VPP). Through this arrangement, the cluster of DER units can exhibit the same level of observability, controllability, and market functionality as traditional transmission-connected power plants [5]-[10].

Power can be distributed through different methods, yet customers seek top-notch quality, minimal expenses, and unparalleled dependability. VPPs stand out as notable solutions for ensuring a dependable electricity supply in a power system. As this system incorporates distributed energy resources (DERs), effective arrangement of these assets becomes crucial [11,12]. It is projected that many market participants engage in numerous activities with this platform [13].

1.1. Definition and concept (Literature Review)

In fact, VPP is currently in the speculation phase and there is no solitary description for the structure of VPP in the literary works. In [14] VPP is characterized identically to an independent micro-grid. In [7], VPP is depicted as a collection of various kinds of spread-out resources that might be scattered across different locations within the medium voltage distribution network. In [15], VPP is comprised of a variety of technologies with diverse operational behaviors and availability, enabling them to link up with different points of the distribution network. In [16] VPP is defined as a multi-technology and multi-location diverse entity. In the FENIX project, the concept of VPP is articulated as follows: "A VPP consolidates the capabilities of numerous distinct DERs, forming a unified operational profile derived from a blend of the characteristics defining each DER, and can factor in the network's influence on the collective output of DERs. A VPP serves as a versatile representation of a collection of DERs that can be utilized for contractual agreements in the wholesale market and for providing services to the system operator [15]."

Here we describe the general idea of the VPP as follows:

A Virtual Power Plant (VPP) is an idea that integrates dispersed generator units combining fossil and renewable sources , controllable loads, and storage systems to function as a unified power entity which managed by an Energy Management System (EMS) through bi-directional communication empowers real-time monitoring and control, elevating operational efficiency, stability and flexibility of distribution grid.

Lately, numerous literary appraisals have been published in the realm of VPP concept, with a specific focus on DERs to address power system concerns. The following section provides a review of some of these publications.

In [17] a comprehensive review of VPP ideas is presented and also offers an overall summary of VPP concepts. Authors of [18] examines the obstacles and issues arising from the discharging or charging of plug-in electrical vehicles. It explores the potential of electric vehicles as a solution for integrating RESs and Demand Response programs (DR) in grid. Reference [19] presents a review of modeling the uncertainty modes used in power system analysis, discussing the strengths and weaknesses of these methods. In [20], the researchers focused on improving the scheduling of a market-driven virtual power plant to increase profitability and reduce procurement costs. In contrast, reference [21] introduced a new market bidding mechanism for VPPs to manage the balancing energy market. Reference [22] assessed a VPP in the energy market combining RESs, ESSs, and demands to optimize societal welfare. Reference [23] studied interconnected AC-DC microgrids to enhance societal welfare, while reference [24] explored VPPs acting as price setters to mitigate real-time market penalties. Additionally, reference [25] investigated a multi-objective bidding scheme for virtual power plants involving Wind Turbines (WTs) and Photovoltaics (PVs), reference [26] put forward a strategy to maximize profits for VPPs in demand response programs, and reference [27] examined the characteristics of virtual power plants providing flexibility services in distribution systems. Furthermore, reference [28] proposed a method for multi-level market contracts defining VPP associations, considering VPP collaboration while addressing uncertainties related to distributed generations. The authors of [29] expanded a model focused on retail to analyze the dispatch capabilities of WTs, PVs, and ESSs to optimize societal welfare for customers. Lastly, the authors of reference [30] evaluated the impact of demand-side management programs along with ESS facilities on the internal power market of VPP and locational marginal prices. Examining different explanations and fundamental concepts of Virtual Power Plants, its key elements, and ultimately two main forms of VPPs, commercial VPPs (CVPPs) and technical VPPs (TVPPs) described in [31].

1.1 Research Gap

In many of the articles discussed in the literature, there are weaknesses and unspoken aspects, one of which is that a virtual power plant does not necessarily take geographical distance into account, and this is its advantage over other smart grid concepts like microgrids. However, this does not mean that any distance is not a concern at all; rather, it refers to, for example, the geographical distance within a distribution or transmission network.

Another aspect is that the idea of a VPP is not solely for the participation of small capacity units in the electricity market, but one of the advantages of this concept is participation in the energy market. It could be argued that one of the main benefits of a VPP is to assist in enhancing the flexibility of the distribution network towards ensuring a more reliable electricity supply.

Failure to consider the consistent output of a VPP when participating in the energy market and other markets is another weakness identified in the literature review. Essentially, most studies on VPPs in the electricity market focus on displaying the dispatch results of units under the virtual power plant's supervision, rather than the monolith output of the VPP every hour of the day and night for market participation or other services.

Additionally, the operator of a VPP and the operator of the distribution network can be the same entity, in which case the VPP, besides considering the operational constraints of the network, is required to supply all its loads. Furthermore, by considering a smaller area within the network, it can aggregate production and supply loads under its supervision and also interact with the upstream distribution network for electricity service trading. Therefore, the realization of the VPP concept is not solely achieved through participation in the electricity market; rather, one of the realizations of the VPP idea is participation in the energy market.

In the following sections, we will provide an overview of the key components and capabilities of a virtual power plant, as well as its types and planning and solving methods.

2. Scheduling Issues Related to Mathematical Model and Optimization Goal

In the power systems, the integration of innovative management techniques and DERs taking into account security, quality, reliability, and power accessibility leads to a shift from static to dynamic grid operations, emphasizing the VPP concept. As DER penetration in power systems grows rapidly, particularly in grid management, offering ancillary services and enhancing grid performance become crucial. Thus, introducing innovative approaches to control generation and facilitate their involvement in electricity markets is essential. The VPP concept emerges as a suitable solution to address these challenges.

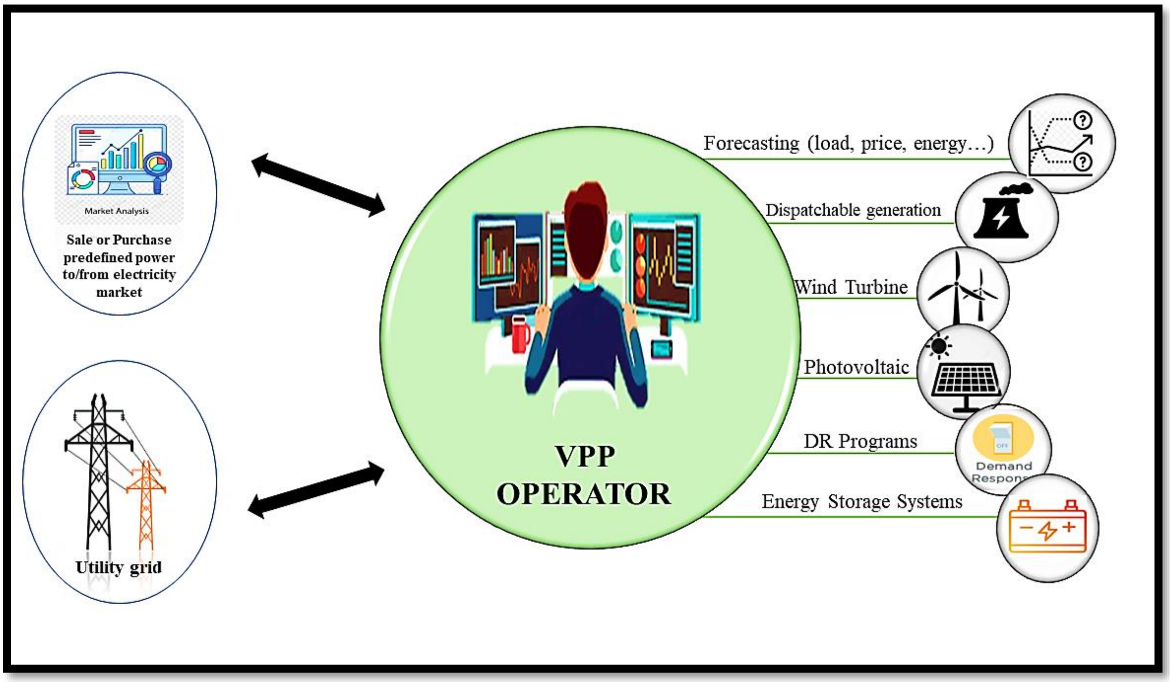

Fig. 1. A Typical VPP structure.

Fig. 1 illustrates the composition of a VPP concerning the aggregation of DERs. In such setup, the aggregator offers a profile of production derived from dealings with various electricity producers, taking into account their anticipated power production profiles. The process depicted in the figure involves numerous intricacies, including predictive algorithms and the coordination of system elements according to their technical and financial characteristics [13].

Overall, two different categories of formulations are typically considered for addressing efficient scheduling challenges: stochastic modeling and deterministic and robust optimization. Stochastic formulations for optimal management problems in VPPs are addressed in references [32-37], and deterministic formulations for VPP frameworks are defined in references [38-42]. A stochastic approach for solving the scheduling and determining optimal bids in a VPP is demonstrated in Fig. 2. This strategy involves receiving various scenarios, minimizing them to a manageable figure, performing stochastic optimization, and deriving optimal energy bids based on the complete stochastic process.

The primary purpose of a VPP is to maximize its revenue by optimizing the scheduling of DERs while adhering to the constraints of the grid. As a VPP curtails or shift its load in DR programs, the reduced load can be considered as virtual generation. Various types of DERs, when operating individually, may lack the capacity, flexibility, and control necessary for effective management for a system and marketing engagements.

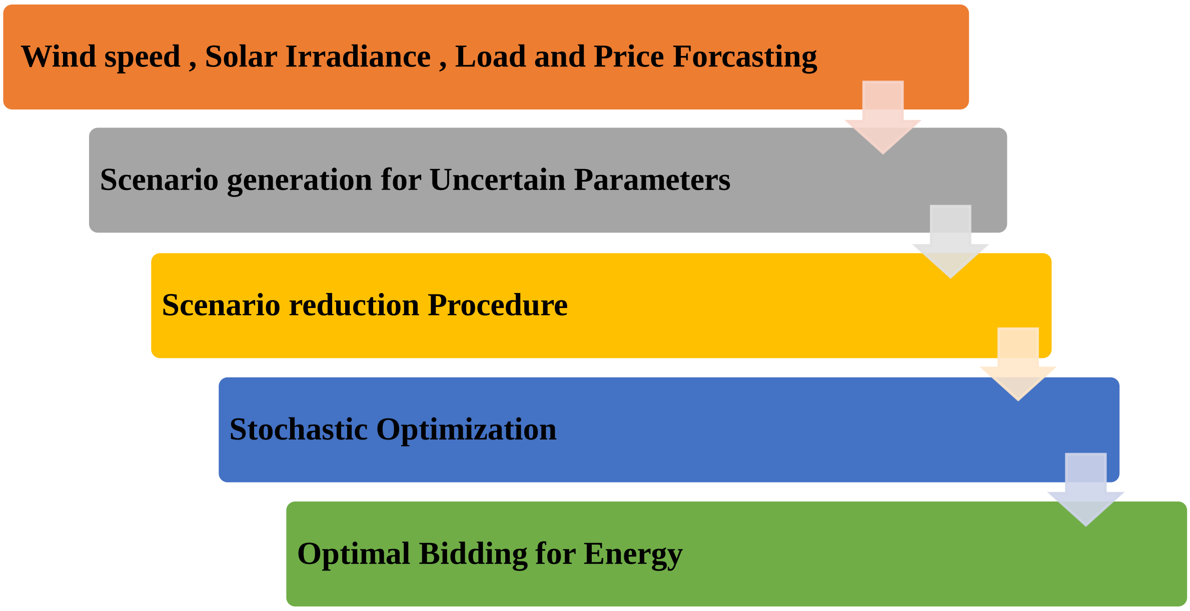

Fig. 2. Optimal energy bidding in a VPP.

This issue Can be tackled through consolidation these resources and flexible load demands into a virtual power plant.

Typically, the scheduling of DERs in a VPP is formulated as an optimization problem, often represented in the form of an equation (Eq. 1). This optimization problem seeks to maximize its profit by determining the optimal operation of DERs, considering factors such as energy production, consumption, market prices, and system constraints. By aggregating multiple DERs and flexible loads into a VPP, the overall efficiency and profitability of the system can be enhanced, enabling better participation in energy markets and grid services [43-44].

$$\begin{gathered}\mathbf{OF} = \boldsymbol{Maximizing\ Profit\ /\ Minimizing\ Cost} \\ \boldsymbol{subject\ to}: \\ \boldsymbol{Diverse\ optional\ and/or\ compulsory\ Constraints} \qquad (\mathbf{1})\end{gathered}$$

3. VPP COMPONENTS

3.1 Generation

The Virtual Power Plant comprises three main components, starting with the Generation Technology. Distributed Generation technologies like Combined Heat and Power (CHP), biomass, small power plants, small-sized hydro-plants, wind energy, solar production, and controllable loads fall under the DG category. DG units can be classified as Domestic Distributed Generators (DDGs) serving individual consumers and Public Distributed Generators (PDGs) injecting power into the grid. Both DDGs and PDGs can include energy storage. DDGs are typically connected to low voltage distribution networks, while PDGs are connected to medium voltage networks. DDGs aim to meet their own energy needs and enhance reliability, while PDGs aim to sell their power to network customers. DDGs have smaller capacities compared to PDGs, limiting their ability to participate in power markets independently. Some DGs, for instance wind turbines (WTs) and photovoltaics (PVs), are stochastic, while others like fuel cells and micro turbines are dispatchable. PDGs and DDGs can be further categorized as Dispatchable PDGs (DPDGs), Stochastic PDGs (SPDGs), Dispatchable DDGs (DDDGs), and Stochastic DDGs (SDDGs) [31].

3.2 Storage facilities

Today, energy storage systems are increasingly recognized as a vital tool for balancing fluctuations in power demand with varying levels of electricity production. Within the realm of RESs, these facilities may function as supplementary energy reservoirs, particularly for non-dispatchable or stochastic production like WTs and PV facilities, particularly in areas with fragile networks. ESSs contemplated for assimilation in VPPs include:

- Battery Energy Storage System (BESS)
- Hydrogen coupled with Fuel Cell (FC) technologies
- Flywheel Energy Storage (FWES)
- Compressed Air Energy Storage (CAES)
- Supercapacitor Energy Storage (SCES)
- Hydraulic Pumped Energy Storage (HPES)
- Superconductor Magnetic Energy Storage (SMES)

These diverse ESS facilities play a pivotal function in enhancing the flexibility and efficiency of VPPs, enabling better assimilation of RESs into the network and ensuring stability in power supply.

3.3 Information Communication Technology (ICT)

Effective communication technologies and foundation are crucial necessities for VPPs. Various communication media facilities might be utilized for intercommunication across Energy Management Systems (EMS), Supervisory Control and Data Acquisition (SCADA), and Distribution Dispatching Center (DCC). These technologies play a vital role in enabling seamless coordination, control, and data exchange within the VPP, ensuring efficient management of power generation, distribution, and monitoring. These systems are used for monitoring and controlling the performance of electricity generation units and for optimizing electricity production consumption planning.

4. TYPES OF VIRTUAL POWER PLANTS

4.1 Technical VPP (TVPP)

The TVPP is a system that comprises DERs from the same geographic area. It incorporates the real time impact within the local grid on the aggregated DERs profile and depicts the cost and operational attributes of the portfolio. The TVPP offers merits and operations such as domestic system administration for the Distribution System Operator (DSO) and provides flexibility and ancillary services for the Transmission System Operator (TSO). Operator of a TVPP needs comprehensive data regarding the local grid, usually obtained from the DSO [47].

Key features of a VPP include [48]:

- Observability of DER units to the network operators
- Involvement of DER units in system oversight

- Maximizing the efficient use of DER unit capacity to offer ancillary services, taking into account limitations within the local network.

By leveraging these capabilities, a VPP enables efficient coordination and utilization of DER resources within a specific geographic area, enhancing overall system flexibility and reliability.

The use of the TVPP concept permits small-sized units to offer ancillary services, thereby reducing risks of unavailability through portfolio diversification and capacity aggregation in contrast to standalone DER units. A detailed analysis of the technological monitoring abilities of DERs and their potential to provide ancillary services is conducted in research studies [49] and [50]. This analysis includes assessing the technological potential by considering the grid-interconnected converter individually with its unique abilities, revealing significant technological opportunities. DSOs implementing the TVPP idea can also operate as Active Distribution Network (ADN) operators [51]. An ADN operator can leverage ancillary services provided by DERs to optimize network performance. Additionally, ADN operators can provide ancillary services to other network operators, enhancing overall system flexibility and reliability. The TVPP concept can lead to the establishment of hierarchical or parallel ADN structures based on various voltage levels or network zones, enabling efficient coordination and utilization of DER resources. Numerous instances of ADNs are cataloged in the active network implementation Register [48].

The TVPP is responsible for performing various essential functions, including continuously monitoring equipment conditions and retrieving historical load data, managing assets with statistical support, enabling self-recognition and qualification of network elements, integrating fault detection coupled with outage management, facilitating maintenance, and conducting statistical analysis for optimization of project portfolios.

4.2 Commercial Virtual Power Plant (CVPP)

A CVPP aggregates the characteristics and results of DER to depict the cost and operational attributes of the DER portfolio. The aggregated CVPP profile does not account for the influence of the distribution network. Services offered by a CVPP encompass wholesale energy market trading, portfolio balancing, and providing services to the transmission system operator through bids and offers. A third-party aggregator or a Balancing Responsible Party (BRP) with market access, like an energy provider, could manage a CVPP. The CVPP facilitates [47,48]:

- Observability of DERs within energy markets,
-allows DERs to participate in wholesale markets,
- maximizes the benefit obtained from the involvement of DER units in wholesale markets.

By enabling market entry for small-sized units and leveraging portfolio diversity and capacity, CVPPs help reduce the risk of imbalance compared to individual DER units operating in isolation. CVPPs focus on commercial aggregation and may not address the network operation aspects crucial for stable operation, as active distribution networks must [52]. The aggregated DERs are not restricted by placement and can be dispersed across different distribution and transmission networks. As a result, a sole distribution network zone might have multiple CVPPs aggregating DER units within its area.

Primary functionalities of a CVPP include optimizing and scheduling generation derived from forecasted consumer load demand and production capacity. Once actual demand deviates from predictions, Demand Response Resources (DRRs) are utilized to bridge the disparity between generation and actual consumption. Additionally, CVPP functions typically involve maintaining and submitting characteristics of DERs, forecasting production and consumption, managing demand during outages, developing bids of DERs, submitting market bidding, daily optimization, and scheduling of generation, and facilitating the sale of energy from DERs to the market.

5. Scheduling Problem Related to Solving Methods

When defining an optimization model for a scheduling problem, several challenges arise in finding a solution. Initially, diverse input data must be gathered, and then an appropriate method needs to be chosen to solve the optimization model. In the context of addressing optimal scheduling problems in VPPs, a variety of methods have been utilized. These approaches could be broadly categorized into two primary approaches: mathematical optimization approaches and heuristic optimization approaches.

solving methods in virtual power plants include optimization algorithms, demand and supply management, energy management, and intelligent systems. The goal of these methods is to improve the efficiency and performance of the virtual power plant and increase flexibility in electricity production. These methods utilize advanced computational and data analysis techniques.

Mathematical optimization methods pertinent to VPPs can be delineated as follows:

- Mixed integer linear programming [33-35]
- Primal-dual sub-gradient algorithm [40]
- Fuzzy simulation and crisp equivalent [42]
- Game theory [49]
- Linear programming [53, 54,55]
- Nonlinear programming [56]
- Event-driven service-oriented framework [56]
- Mixed integer nonlinear programming [57, 58]
- Point estimate method [34, 57]
- Interior point method and primal-dual sub-gradient algorithm [39,59]
- Branch-and-bound method [60, 61]
- Decision Tree [32, 62]
- Hierarchical structure [63, 64]
- Dynamic programming [65]
- Quadratic programming [60, 66]
- Area-based observe and focus algorithm [67]

6. CONCLUSION

The VPP idea enables individual DERs to access and participate in various energy markets, Leveraging VPP market intelligence for optimization their positions and maximizing income possibilities. This approach benefits grid operations by efficiently utilizing available capacity and enhancing overall operational efficiency. Stakeholders across different sectors stand to gain from the Virtual Power Plant concept:

Owners of DERs:
- Capture flexibility value
- Increase asset value
- Reduce financial risk
- Improve negotiation abilities

DSOs and TSOs:
- Gain visibility of DERs
- Utilize control flexibility
- Enhance grid investments
- Coordinate DSO and TSO efforts
- Address operational complexities

Policy Makers:
- Integrate renewables cost-effectively
- Open energy markets to small-scale participants
- Enhance system efficiency
- Support renewable energy goals
- Improve consumer choice
- Create new job opportunities

Suppliers and aggregators:
- Offer new services
- Reduce commercial risk
- Explore new business opportunities

Hence, it is crucial to emphasize that a virtual power plant serves as both a strategic concept for the integration of low-capacity units into the electricity market and as an autonomous entity for the planning, optimization, and efficient aggregation of dispatchable and non-dispatchable units, as well as demand response programs at the distribution network level that upon its specific application it serves as technical or commercial type.

REFERENCES

[1] El Bakari, K., & Kling, W. L. (2010, October). Virtual power plants: An answer to increasing distributed generation. In *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)* (pp. 1-6). IEEE.

[2] J.O. Wara: Current status and Evaluation of Electricity market liberalization in Japan, USA and Europe. IEE 391st regular research session, May 2005.

[3] Friedman, N. Richard. "Distributed energy resources interconnection systems: Technology review and research needs." (2002).

[4] Ropenus, Stephanie, and Klaus Skytte. "Regulatory review and barriers for the electricity supply system for distributed generation in EU-15." *2005 International Conference on Future Power Systems*. IEEE, 2005.

[5] Dauensteiner, A. "European Virtual Fuel Cell Power Plant–Management summary report." *Germany, NNE5-2000-208* (2007).

[6] Caldon, Roberto, Andrea Rossi Patria, and Roberto Turri. "Optimal control of a distribution system with a virtual power plant." *Bulk power system dynamics and control, Cortina. d'Ampezzo, Italy* (2004): 18.

[7] Bignucolo, F., et al. "The voltage control on MV distribution networks with aggregated DG units (VPP)." *Proceedings of the 41st International Universities Power Engineering Conference*. Vol. 1. IEEE, 2006.

[8] Wu, Felix F., Khosrow Moslehi, and Anjan Bose. "Power system control centers: Past, present, and future." *Proceedings of the IEEE* 93.11 (2005): 1890-1908.

[9] Kamphuis, I. G., et al. *Massive coordination of residential embedded electricity generation and demand response using the PowerMatcher approach*. Petten: ECN, 2007.

[10] Skovmark, Rasmus, and Johan Holkmann Jacobsen. *Analysis, Design and Development of a Generic Framework for Power Tradin*. Diss. M. Sc thesis, available from Technical University of Denmark, 2007.

[11] Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, *65*, 1-17.

[12] Mancarella, P. (2012, July). Smart multi-energy grids: concepts, benefits and challenges. In *2012 IEEE Power and Energy Society General Meeting* (pp. 1-2). IEEE.

[13] Nosratabadi, S. M., Hooshmand, R. A., & Gholipour, E. (2017). A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems. *Renewable and Sustainable Energy Reviews*, *67*, 341-363.

[14] Morais, Hugo, et al. "VPP operating in the isolated grid." *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*. IEEE, 2008.

[15] Pudjianto, Danny, Charlotte Ramsay, and Goran Strbac. "Virtual power plant and system integration of distributed energy resources." *IET Renewable power generation* 1.1 (2007): 10-16.

[16] Morais, Hugo, et al. "A decision-support simulation tool for virtual power producers." *2005 International Conference on Future power Systems*. IEEE, 2005.

[17] Nikonowicz, Ł., & Milewski, J. (2012). Virtual Power Plants-general review: structure, application and optimization. *Journal of power technologies*, *92*(3).

[18] Aghaei, J., Nezhad, A. E., Rabiee, A., & Rahimi, E. (2016). Contribution of plug-in hybrid electric vehicles in power system uncertainty management. *Renewable and Sustainable Energy Reviews*, *59*, 450-458.

[19] Aien, M., Hajebrahimi, A., & Fotuhi-Firuzabad, M. (2016). A comprehensive review on uncertainty modeling techniques in power system studies. *Renewable and Sustainable Energy Reviews*, *57*, 1077-1089.

[20] Bai, H., Miao, S., Ran, X., & Ye, C. (2015). Optimal dispatch strategy of a virtual power plant containing battery switch stations in a unified electricity market. *Energies*, *8*(3), 2268-2289.

[21] Mazzi, N., Trivella, A., & Morales, J. M. (2018). Enabling active/passive electricity trading in dual-price balancing markets. *IEEE Transactions on Power Systems*, *34*(3), 1980-1990.

[22] Ullah, Z., & Mirjat, B. (2022). M.(2022). Optimisation and Management of Virtual Power Plants Energy Mix Trading Model. *International Journal of Renewable Energy Development*.

[23] Baseer, M., Mokryani, G., Zubo, R. H., & Cox, S. (2019). Planning of HMG with high penetration of renewable energy sources. *IET Renewable Power Generation*, *13*(10), 1724-1730.

[24] Hu, J., Jiang, C., & Liu, Y. (2019). Short-term bidding strategy for a price-maker virtual power plant based on interval optimization. *Energies*, *12*(19), 3662.

[25] Khaloie, H., Abdollahi, A., Shafie-Khah, M., Siano, P., Nojavan, S., Anvari-Moghaddam, A., & Catalão, J. P. (2020). Co-optimized bidding strategy of an integrated wind-thermal-photovoltaic system in deregulated electricity market under uncertainties. *Journal of Cleaner Production*, *242*, 118434.
[26] Pasetti, M., Rinaldi, S., & Manerba, D. (2018). A virtual power plant architecture for the demand-side management of smart prosumers. *Applied Sciences*, *8*(3), 432.
[27] Ullah, Z., & Mirjat, N. H. (2022). Modelling and analysis of virtual power plants interactive operational characteristics in distribution systems. *Energy Conversion and Economics*, *3*(1), 11-19.
[28] Liu, J., Tang, H., Xiang, Y., Liu, J., & Zhang, L. (2017). Multi-stage market transaction method with participation of virtual power plants. *Electr. Power Constr*, *38*, 137-144.
[29] Ullah, Z., & Baseer, M. (2022). Operational planning and design of market-based virtual power plant with high penetration of renewable energy sources. *Int. J. Renew. Energy Dev*, *11*, 620-629.
[30] Ullah, Z., Arshad, & Hassanin, H. (2022). Modeling, optimization, and analysis of a virtual power plant demand response mechanism for the internal electricity market considering the uncertainty of renewable energy sources. *energies*, *15*(14), 5296.
[31] Saboori, H., Mohammadi, M., & Taghe, R. (2011, March). Virtual power plant (VPP), definition, concept, components and types. In *2011 Asia-Pacific power and energy engineering conference* (pp. 1-4). IEEE.
[32] Moutis, P., & Hatziargyriou, N. D. (2014). Decision trees-aided active power reduction of a virtual power plant for power system over-frequency mitigation. *IEEE Transactions on Industrial Informatics*, *11*(1), 251-261.
[33] Kardakos, E. G., Simoglou, C. K., & Bakirtzis, A. G. (2015). Optimal offering strategy of a virtual power plant: A stochastic bi-level approach. *IEEE Transactions on Smart Grid*, *7*(2), 794-806.
[34] Shabanzadeh, M., Sheikh-El-Eslami, M. K., & Haghifam, M. R. (2016). A medium-term coalition-forming model of heterogeneous DERs for a commercial virtual power plant. *Applied Energy*, *169*, 663-681.
[35] Thavlov, A., & Bindner, H. W. (2014). Utilization of flexible demand in a virtual power plant set-up. *IEEE Transactions on Smart Grid*, *6*(2), 640-647.
[36] Zamani, A. G., Zakariazadeh, A., & Jadid, S. (2016). Day-ahead resource scheduling of a renewable energy based virtual power plant. *Applied Energy*, *169*, 324-340.
[37] Wang, Y., Ai, X., Tan, Z., Yan, L., & Liu, S. (2015). Interactive dispatch modes and bidding strategy of multiple virtual power plants based on demand response and game theory. *IEEE Transactions on Smart Grid*, *7*(1), 510-519.
[38] Dietrich, K., Latorre, J. M., Olmos, L., & Ramos, A. (2015). Modelling and assessing the impacts of self-supply and market-revenue driven Virtual Power Plants. *Electric Power Systems Research*, *119*, 462-470.
[39] Yuan, Y., Wei, Z., Sun, G., Sun, Y., & Wang, D. (2014). A real-time optimal generation cost control method for virtual power plant. *Neurocomputing*, *143*, 322-330.
[40] Yu, J., Jiao, Y., Wang, X., Cao, J., & Fei, S. (2015). Bi-level optimal dispatch in the Virtual Power Plant considering uncertain agents number. *Neurocomputing*, *167*, 551-557.
[41] Mnatsakanyan, A., & Kennedy, S. W. (2014). A novel demand response model with an application for a virtual power plant. *IEEE Transactions on Smart Grid*, *6*(1), 230-237.
[42] Fan, S., Ai, Q., & Piao, L. (2016). Fuzzy day- ahead scheduling of virtual power plant with optimal confidence level. *IET Generation, Transmission & Distribution*, *10*(1), 205-212.
[43] Moghaddam, I. G., Nick, M., Fallahi, F., Sanei, M., & Mortazavi, S. (2013). Risk-averse profit-based optimal operation strategy of a combined wind farm–cascade hydro system in an electricity market. *Renewable energy*, *55*, 252-259.
[44] Wille-Haussmann, B., Erge, T., & Wittwer, C. (2010). Decentralised optimisation of cogeneration in virtual power plants. *Solar Energy*, *84*(4), 604-611.
[45] Mashhour, E., & Moghaddas-Tafreshi, S. M. (2010). Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: Problem formulation. *IEEE Transactions on Power Systems*, *26*(2), 949-956.
[46] Mashhour, E., & Moghaddas-Tafreshi, S. M. (2010). Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part II: Numerical analysis. *IEEE Transactions on Power Systems*, *26*(2), 957-964.
[47] Pudjianto, D., Ramsay, C., Strbac, G., & Durstewitz, M. (2008). The virtual power plant: Enabling integration of distributed generation and demand. *fenix Bulletin*, *2*, 10-16.
[48] Braun, M. (2009). Virtual power plants in real applications. *Sixth Research Framework Programme of the European Union for the FENIX project (SES6–518272)*.

[49] Braun, M. (2009). *Provision of ancillary services by distributed generators: Technological and economic perspective* (Vol. 10). kassel university press GmbH.

[50] Braun, M. (2007). Technological control capabilities of DER to provide future ancillary services. *International journal of distributed energy resources*, *3*(3), 191-206.

[51] Braun, M., & Strauss, P. (2008). A review on aggregation approaches of controllable distributed energy units in electrical power systems. *International Journal of Distributed Energy Resources*, *4*(4), 297-319.

[52] Friedman, N. R. (2002). Distributed energy resources interconnection systems: Technology review and research needs.

[53] Vasirani, M., Kota, R., Cavalcante, R. L., Ossowski, S., & Jennings, N. R. (2013). An agent-based approach to virtual power plants of wind power generators and electric vehicles. *IEEE Transactions on Smart Grid*, *4*(3), 1314-1322.

[54] Arslan, O., & Karasan, O. E. (2013). Cost and emission impacts of virtual power plant formation in plug-in hybrid electric vehicle penetrated networks. *Energy*, *60*, 116-124.

[55] Soltani, M., Raoofat, M., & Rostami, M. A. (2012, May). Optimal reliable strategy of virtual power plant in energy and frequency control markets. In *2012 Proceedings of 17th Conference on Electrical Power Distribution* (pp. 1-6). IEEE.

[56] Sučić, S., Dragičević, T., Capuder, T., & Delimar, M. (2011). Economic dispatch of virtual power plants in an event-driven service-oriented framework using standards-based communications. *Electric Power Systems Research*, *81*(12), 2108-2119.

[57] Peik-Herfeh, M., Seifi, H., & Sheikh-El-Eslami, M. K. (2013). Decision making of a virtual power plant under uncertainties for bidding in a day-ahead market using point estimate method. *International Journal of Electrical Power & Energy Systems*, *44*(1), 88-98.

[58] Morais, H., Sousa, T., Faria, P., & Vale, Z. (2013, July). Reactive power management strategies in future smart grids. In *2013 IEEE Power & Energy Society General Meeting* (pp. 1-5). IEEE.

[59] Yang, H., Yi, D., Zhao, J., Luo, F., & Dong, Z. (2014). DISTRIBUTED OPTIMAL DISPATCH OF VIRTUAL POWER PLANT BASED ON ELM TRANSFORMATION. *Journal of industrial & management optimization*, *10*(4).

[60] Shafie-khah, M., Moghaddam, M. P., Sheikh-El-Eslami, M. K., & Rahmani-Andebili, M. (2012). Modeling of interactions between market regulations and behavior of plug-in electric vehicle aggregators in a virtual power market environment. *Energy*, *40*(1), 139-150.

[61] Giuntoli, M., & Poli, D. (2013). Optimized thermal and electrical scheduling of a large scale virtual power plant in the presence of energy storages. *IEEE Transactions on Smart Grid*, *4*(2), 942-955.

[62] Moutis, P., & Hatziargyriou, N. D. (2014). Decision trees aided scheduling for firm power capacity provision by virtual power plants. *International Journal of Electrical Power & Energy Systems*, *63*, 730-739.

[63] Skarvelis-Kazakos, S., Rikos, E., Kolentini, E., Cipcigan, L. M., & Jenkins, N. (2013). Implementing agent-based emissions trading for controlling Virtual Power Plant emissions. *Electric Power Systems Research*, *102*, 1-7.

[64] Bie, Z., Zhang, P., Li, G., Hua, B., Meehan, M., & Wang, X. (2012). Reliability evaluation of active distribution systems including microgrids. *IEEE Transactions on power systems*, *27*(4), 2342-2350.

[65] Molderink, A., Bakker, V., Bosman, M. G., Hurink, J. L., & Smit, G. J. (2010). Management and control of domestic smart grid technology. *IEEE transactions on Smart Grid*, *1*(2), 109-119.

[66] Petersen, M., Bendtsen, J., & Stoustrup, J. (2012, June). Optimal dispatch strategy for the agile virtual power plant. In *2012 American Control Conference (ACC)* (pp. 288-294). IEEE.

[67] Tascikaraoglu, A., Erdinc, O., Uzunoglu, M., & Karakas, A. (2014). An adaptive load dispatching and forecasting strategy for a virtual power plant including renewable energy conversion units. Applied energy, 119, 445-453.